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# Thin Film Heat Flux Sensors: Design and Methodology

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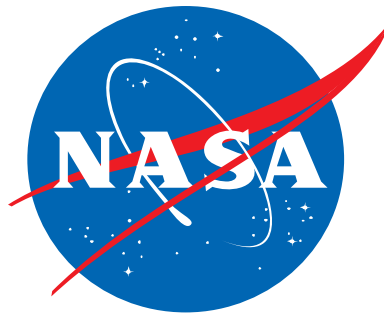
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# Presenter

## Gustave Fralick



- NASA Glenn Research Center
- R&T Sensors and Electronics Branch
- Physical Sensors Instrumentation Research
- Expertise: Thin Film High Temperature Sensors



# Introduction:

- Heat flux is one of a number of parameters, together with pressure, temperature, flow, etc. of interest to engine designers and fluid dynamists
- The measurement of heat flux is of interest in directly determining the cooling requirements of hot section blades and vanes
- In addition, if the surface and gas temperatures are known, the measurement of heat flux provides a value for the convective heat transfer coefficient that can be compared with the value provided by CFD codes

# Heat Flux Sensor Designs

- There are various designs of heat flux sensors such as Gardon gauges, plug gauges, thin film thermocouple arrays, and thin film Wheatstone bridge design
- The use of thin film sensors has several advantages over wire or foil sensors:
  - Thin film sensors do not require special machining of the components upon which they are mounted, and, with thicknesses generally less than 10 microns, they are much thinner than wires or foils.
  - Thin film sensors are thus much less disturbing to the operating environment, and have minimal impact on the physical and thermal characteristics of the supporting structure.
- The two thin film designs will be described

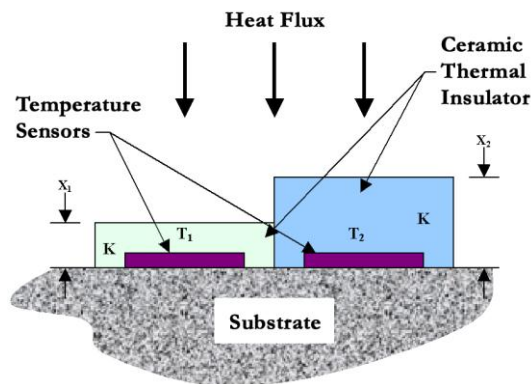
# Thermopile Thin Film Heat Flux Sensors

- In general, the operation of a heat flux sensor depends on Fourier's law of thermal conduction:

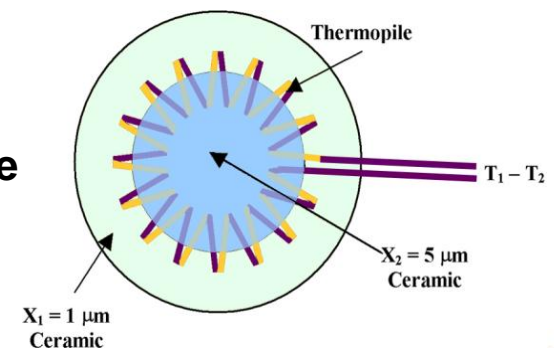
$$Q = -k (dT/dx) \approx -k (\Delta T/\Delta x)$$

- One measures the temperature difference  $\Delta T$  across a known thickness  $\Delta x$  of material whose thermal conductivity  $k$  is also known and then the heat flux  $Q$  is determined
- In the thermopile design, the temperature difference under two different thicknesses of material is used, as shown in figures 1 & 2:

**Figure 1.**  
Thin film  
heat flux  
sensor  
theory of  
operation.



**Figure 2.**  
Thin film  
thermopile  
heat flux  
sensor

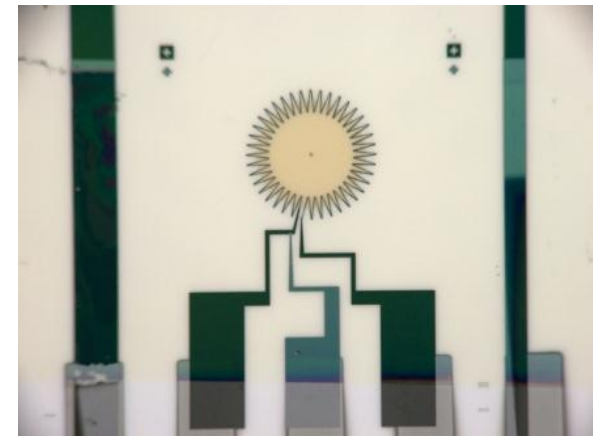


# Thermopile Thin Film Heat Flux Sensors

- Fabrication:
  - A thin film thermopile is deposited on the substrate, as shown in the figures
  - If necessary, an electrically insulating layer is deposited first
  - A layer of low thermal conductivity material such as zirconia is deposited over the inner junctions (as shown in figure 2)
  - The low thermal conductivity layer creates a temperature difference between the inner and outer junctions
- Methodology:
  - The temperature difference ( $T_1 - T_2$  in figure 1) is:
$$\Delta T = T_1 - T_2 = Q\{(x_2 - x_1)/k\}$$
  - Typically,  $x_2 = 5\mu\text{m}$ ,  $x_1 = 1\mu\text{m}$ ,  $k = 1.4 \text{ W/m/K}$  (zirconia)
  - Thus for  $Q = 1 \text{ W/cm}^2 = 10^4 \text{ W/m}^2 \rightarrow \Delta T \approx 29 \text{ mK}$

# Thermopile Thin Film Heat Flux Sensors

- For high temperature operation, one would fabricate the thermopile of type R or S thermocouples (PtRh-Pt), whose output is about  $6 \mu\text{V/K}$ 
  - For a 40 element thermopile, the signal is  $(6 \mu\text{V/K}) \times (29 \times 10^{-3} \text{ K/W/cm}^2) \times 40 \approx 7 \mu\text{V/W/cm}^2$
- Some work has been done in replacing noble metal thermocouples with high temperature ceramics (figure 3)
  - Higher outputs
    - $\sim 100 \mu\text{V/K}$  for  $\text{CrSi}_2\text{-MoSi}_2$
    - $\sim 900 \mu\text{V/K}$  for  $\text{ZnO-In}_2\text{O}_3$
  - Stable at high temperatures
  - May exhibit hysteresis
  - Still in the experimental stage



**Figure 3. Silicide-based heat flux sensor on alumina**

# Wheatstone Bridge Heat Flux Sensors

- In the bridge designs, the temperature difference across a  $\Delta x$  is measured by measuring the resistance change in one or more arms of a Wheatstone bridge
- In the double-sided design, two arms of the bridge are on top of a substrate and the other two are on the bottom (Figures 4 and 5)

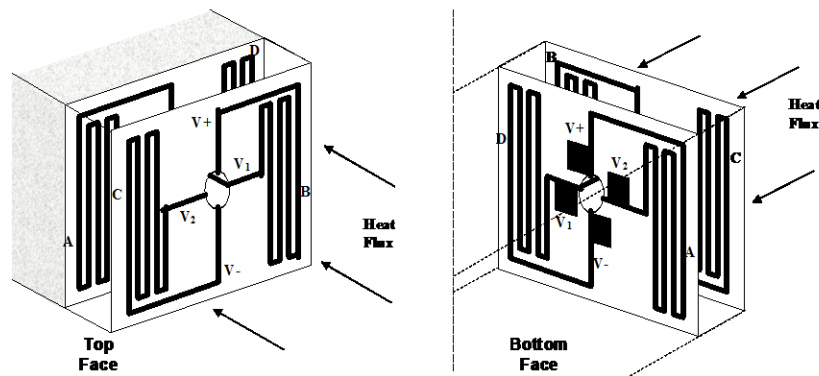


Figure 4: Double-Sided Thin Film Wheatstone Bridge Heat Flux Sensor concept

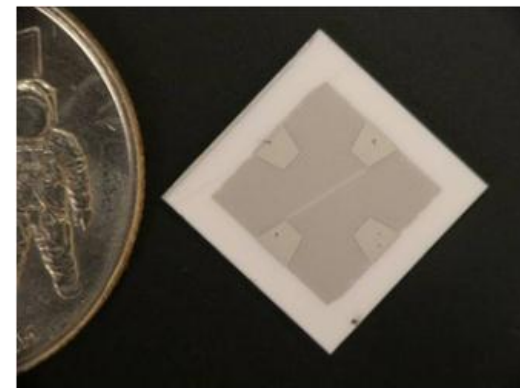


Figure 5: Double sided Pt on alumina sensor for CEV TPS



# Wheatstone Bridge Heat Flux Sensors

- In a single-sided bridge design (Figure 6), all arms are on the same side of the substrate, two with different thicknesses of thermal insulation than the other two
- A high temperature sensor designed to measure the heat flux into the wall of a pulse detonation engine (PDE) has been fabricated (Figure 7)

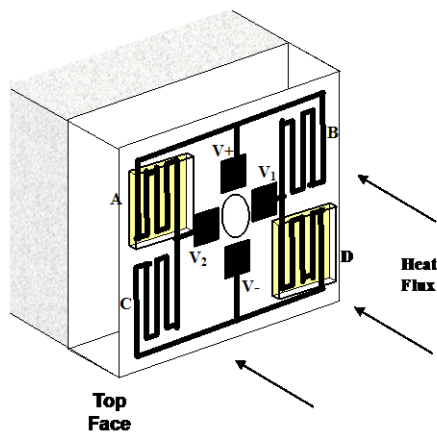


Figure 6. Single-Sided Thin Film Wheatstone Bridge Heat Flux Sensor



Figure 7. PDE Heat flux sensor utilizing a resistance bridge

# Wheatstone Bridge Heat Flux Sensors

- Methodology

- For the situation where a sensor of thickness  $l$  and thermal conductivity  $k_1$  is to measure the heat flux into a substrate of thickness  $L$  and thermal conductivity  $k_2$ , the signal is

$$V_{SIG} = \frac{V\beta Q \frac{l}{k_1}}{2 + \beta Q \left( \frac{l}{k_1} + 2 \frac{L}{k_2} \right)}$$

where  $V$  is the bridge excitation voltage,  $\beta$  is the temperature coefficient of resistance of the bridge material and  $Q$  is the heat flux

- Typically, for the two sided gauge,  $l = 0.040'' = 1.016 \times 10^{-3}$  m,  $L = 1'' = 2.54 \times 10^{-2}$  m,  $k_1 = 36$  W/m/K ( $Al_2O_3$ ),  $k_2 = 15$  W/m/K (type 304 stainless) and  $\beta = 3.98 \times 10^{-3}$  K<sup>-1</sup> (Pt)
- Then, with a bridge excitation  $V$  of one volt and a heat flux  $Q$  of 1 W/cm<sup>2</sup> =  $10^4$  W/m<sup>2</sup>,  $V_{SIG} = 528$  (μV/V)/(W/cm<sup>2</sup>)

# Wheatstone Bridge Heat Flux Sensors

- Methodology (con't):
  - With no heat flux applied to the sensor, all of the bridge elements (A, B, C & D in figure 6) are at the initial temperature  $T_0$ , and have resistance  $R_0$ .
  - With the application of heat flux, the two elements of the bridge not covered by the layer of thermal resistance (B & C) are at a surface temperature designated  $T_S$ , and the other two elements under the film of thermal resistance (A & D) are at the temperature  $T_F < T_S$ .
  - The resistance of the elements are then respectively  $R_0[1 + \beta(T_S - T_0)]$  and  $R_0[1 + \beta(T_F - T_0)]$ , where  $\beta$  is the linear temperature coefficient of resistance.

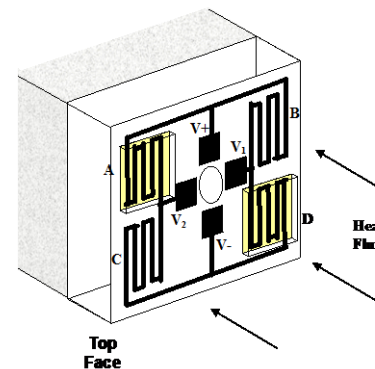


Figure 6. Single-Sided Thin Film Wheatstone Bridge Heat Flux Sensor

# Wheatstone Bridge Heat Flux Sensors

- Methodology (con't):

- With a bridge excitation of  $V$  (volts), the output from one arm is:

$$V_1 = V \frac{R_0 [1 + \beta(T_F - T_0)]}{R_0 [1 + \beta(T_S - T_0)] + R_0 [1 + \beta(T_F - T_0)]}$$

and from the other arm is:

$$V_2 = V \frac{R_0 [1 + \beta(T_S - T_0)]}{R_0 [1 + \beta(T_S - T_0)] + R_0 [1 + \beta(T_F - T_0)]}$$

- The output from the sensor is then

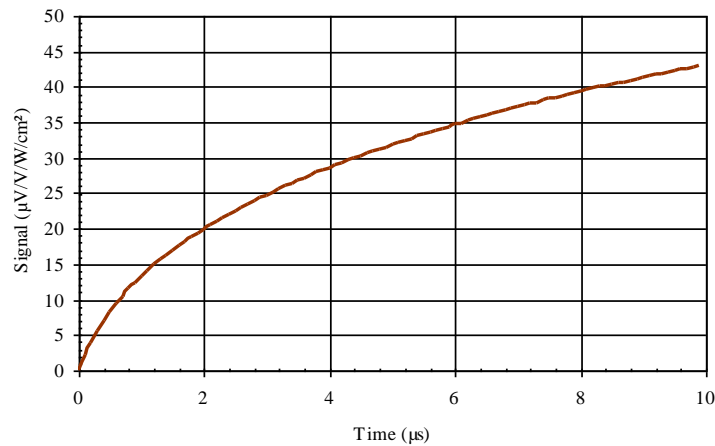
$$V_{SIG} = V_2 - V_1 = V \frac{\beta(T_S - T_F)}{2 + \beta[(T_F - T_0) + (T_S - T_0)]}$$

(Notice that,  $R_0$ , the initial value of the resistance, cancels.)

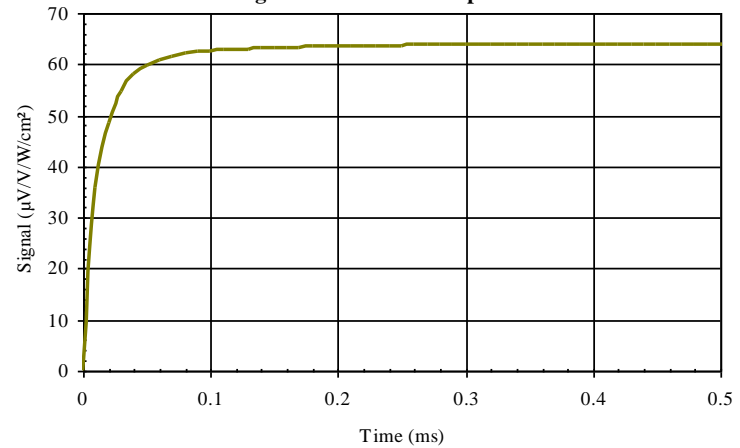
- For the one sided gauge shown in Figure 7, one would typically sputter approximately  $5 \mu\text{m}$   $\text{SiO}_2$  ( $k_1 = 1.4 \text{ W/m/K}$ ) over the appropriate arms of the bridge
- In this case, the output is approximately  $68 (\mu\text{V/V})/(\text{W/cm}^2)$

# Modeled Transient Response

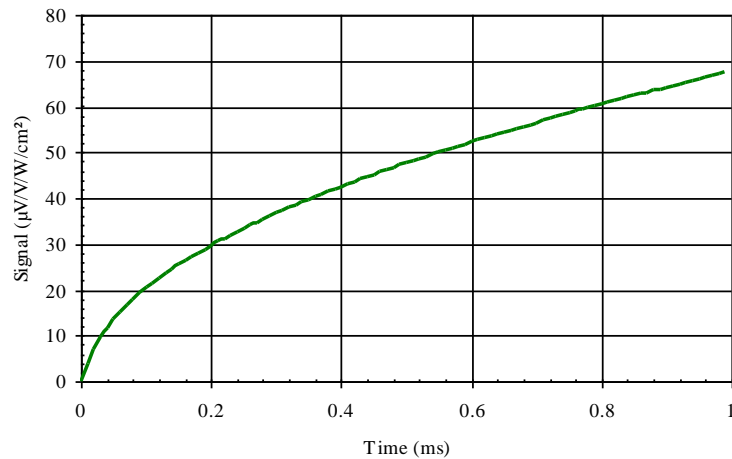
**Single-Sided Thin Film Heat Flux Sensor  
Short-Term Transient Response**



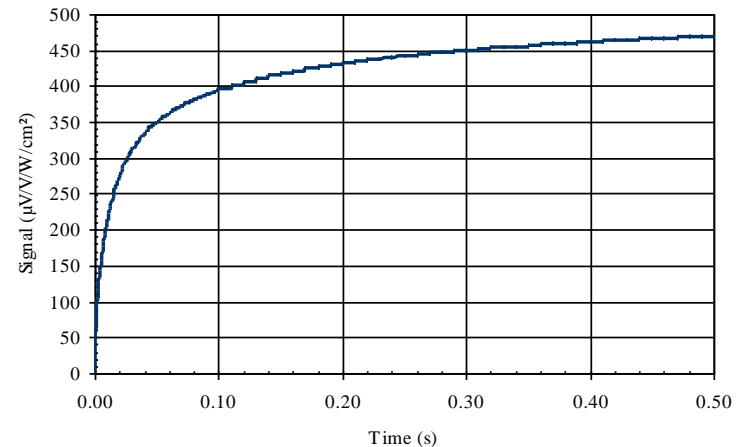
**Single-Sided Thin Film Heat Flux Sensor  
Long-Term Transient Response**



**Double-Sided Thin Film Heat Flux Sensor  
Short-Term Transient Response**



**Double-Sided Thin Film Heat Flux Sensor  
Long-Term Transient Response**



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